this area as an adaptation to the shortage of raw material (*10*), at the same time producing the specialized, light, and efficient tools needed by the hunting parties.

Pyrotechnology has been practiced regularly through human history and throughout the world (*11*) to increase the quality and efficiency of stone tool manufacturing. Although intentionally heated artifacts are common between 14,000 and 10,000 years ago in Europe, they are extremely rare before that. The discovery by Brown *et al*. of heat-treated artifacts in South Africa dating back perhaps 164,000 years (*3*) suggests that the technique was first discovered in Africa.

The development of heat treatment was a substantial technological advance by early humans. Its continued use up to the present day is a testament to the degree to which it allowed people to more effectively control their environment, and also probably contributed to human cognitive development through the beautification of the artifacts it helped produce.

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ASTRONOMY

Gamma-Ray Pulsars Old and New

The Fermi Gamma-ray Space Telescope is discovering neutron stars that are high-energy gamma-ray emitters.

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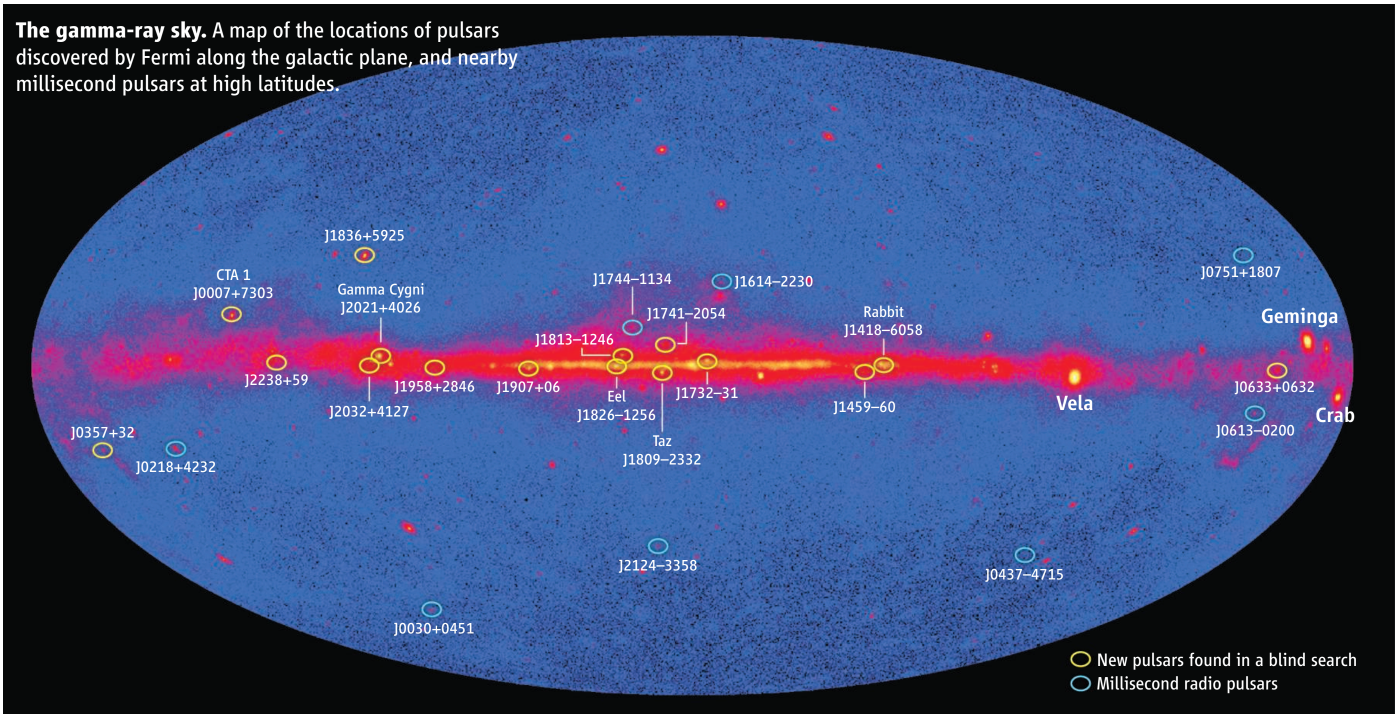
A flood of results from the Fermi Gamma-ray Space Telescope, launched on 11 June 2008, is changing the way that we view neutron stars. The Large Area Telescope (LAT), the main instrument on Fermi, detects photons of energy between 0.1 and 100 GeV emitted from spinning neutron stars known as radio pulsars, from supermassive black holes in the "blazar" class of active galactic nuclei, and from other high-energy sources. By timing the arrival of photons from gamma ray–bright points in the Galaxy, Fermi is discovering new pulsars whose existence was only conjectured. Sixteen such "gamma ray–only" pulsars, rotating between 2 and 20 times per second, are reported on page 840 in this issue (*1*). In a companion paper on page 848, the detection of pulsed gamma rays from eight nearby radio "millisecond pulsars" rotating faster than 200 times per second is described (*2*). Complementing these discoveries, Fermi has detected a steady glow of gamma rays from the globular star cluster 47 Tucanae, as described on page 845 (*3*); this region is thought to harbor dozens of millisecond pulsars.

By the early 1960s, considerable theoretical effort had gone into calculating the structure of neutron stars and their x-ray emitting temperatures. A new field of astronomy was born in 1962 when x-ray sources farther than the Sun were discovered. It was not until the 1970s that



The gamma-ray sky. A map of the locations of pulsars discovered by Fermi along the galactic plane, and nearby millisecond pulsars at high latitudes.

CREDIT: NASA/DOE/INTERNATIONAL LAT TEAM

many x-ray sources were recognized to be pulsars in binary systems, with accretion of matter from a normal stellar companion keeping them hotter and more luminous than was possible for an isolated neutron star.

Although the idea that a neutron star would retain a huge magnetic field by flux conservation during collapse was recognized, the other essential property—that it would be spinning rapidly—seems not to have occurred to anyone until shortly before the discovery of radio pulsars in 1967. Franco Pacini put magnetic field and spin together, and proposed that the rotational energy of a neutron star could be tapped by the emission of electromagnetic waves. The periodic radio blips from pulsars, ever so gradually slowing down, were soon attributed to beams from isolated rotating neutron stars by Thomas Gold in 1968.

The high voltage generated by a spinning magnetic field is what accelerates particles to energies capable of emitting gamma rays. Gamma-ray detections of pulsars began in the 1970s, but only six, including the Crab, were known until last year. The Fermi LAT is the first gamma-ray telescope that is large enough to discover new pulsars on its own.

The LAT is not a telescope in the conventional sense, because gamma-ray photons cannot be focused. Rather, a gamma ray produces an electron-positron pair in one of several layers of tungsten, and alternating silicon planes track those particles, which point back to the direction from which the gamma ray came. Whereas ordinary telescopes can observe only one pulsar at a time, the LAT views 20% of the celestial sphere, and it is rotated in synchrony with its orbit around Earth to scan the entire sky every 3 hours. Recording the direction and arrival time of every pulsar photon, while detecting hundreds of other gamma-ray sources and rejecting unwanted background particles, the LAT accomplishes a remarkable feat of multitasking (see the figure).

Even today, the vast majority of more than 1800 known pulsars are detected only at radio wavelengths, even though gamma-ray luminosities exceed their radio power by several orders of magnitude. With an effective area less than 1 m^2, the LAT can collect only a few hundred photons from a typical source in a few months of operation. In this time, the candidate pulsar may have rotated more than a hundred million times at an unknown frequency that is also slowing down at an unknown rate. The photons from every such promising source were analyzed for periodicity, a computational tour de force that has already revealed 16 new pulsars (*1*) while avoiding false positive detections.

Fermi is discovering mostly young pulsars, including ones inside supernova remnants and synchrotron nebulae, the telltale birth sites of neutron stars that until now had "gone missing." The age of a pulsar is conveniently estimated by dividing its present rotation frequency by its rate of change. The ages of the newly discovered gamma-ray pulsars suggest that the gamma-ray emission mechanism must cease before the radio emission does. As the rotation frequency of a pulsar decreases, so does its spin-down power. But while they are alive, their gamma-ray efficiency, expressed as a percentage of spin-down power, increases up to their death. Although several of the LAT pulsars were born during the latest ice age, the oldest one, PSR J1836+5925, is about 1.8 million years old and is channeling almost all of its power into gamma rays.

Unlike narrow radio beams, gamma rays appear to be emitted in a broad fan that is visible from most directions. This explains why so many pulsars were not detected in radio, and means that they are even more efficient gamma-ray engines than previously thought. The LAT also measures spectra, from which it is inferred that gamma rays are created far above the surface of the neutron star as some models have predicted, where they escape absorption by the strong magnetic field. Millisecond pulsars (*2*) seem to rely on the same physics as ordinary pulsars, even though they are billions of years old. Their spin was "recycled" during a long process of accretion from a companion star, and their weaker magnetic fields allow them to conserve that rotational energy for a longer time. Still, a substantial fraction of their power goes into gamma rays. Dense globular clusters are breeding grounds for millisecond pulsars because of their frequent stellar exchanges. The steady flux of gamma rays detected from the globular cluster 47 Tucanae (*3*) is consistent with dozens of millisecond pulsars having similar gamma-ray efficiencies as the nearby ones.

Fermi has already detected about 20 known young radio pulsars (*2*). Its next goal is to find millisecond pulsars that are radio-quiet, a difficult task because of their rapid rotation. Pulsars detected by Fermi are solving another mystery, the origin of TeV ($>10^{12}$ eV) gamma-ray emission in the galactic plane. Most of the diffuse patches of TeV emission can be associated with Fermi pulsars (*4*), which must release energetic particles into the interstellar medium. The TeV frontier in astrophysics is the latest, but probably not the last, in which pulsars will be implicated. Neutron stars may be small, but they are worth our effort. Unlike black holes, they give a lot back.

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ENGINEERING

Cellulosic Biofuels—Got Gasoline?

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Several routes are being developed to convert biomass into hydrocarbon fuels instead of ethanol.

Most people think of ethanol as the only liquid biofuel, and that the major advances in biofuels will revolve around enzymatic conversion of cellulosic or woody biomass (including nonfood stems and stalks of corn stover or switchgrass, and wood chips) into simple fermentable sugars (*1*). However, in just a few years the commercial scale production of liquid hydrocarbons from biomass will be possible. Hydrocarbons can be made (see the figure) from the sugars of woody biomass through microbial fermentation or liquid-phase catalysis, or directly from woody biomass through pyrolysis or gasification (*2*). Finally, lipids from nonfood crops as well as algae (*3*) can be converted to hydrocarbons. The resulting hydrocarbon biofuels will be drop-in replacements for gasoline, diesel, and jet fuel; will give much higher gas mileage than ethanol; and will work in existing engines and distribution networks.

Ethanol produced from biomass is already used in automotive fuels in the United States as a high-octane, oxygenated additive to improve combustion, which allows clean air standards to be met. The drawback to using ethanol as a complete replacement for gaso-

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